

Atty. Dkt. 2689-8
BAIK-230090/US/K

U.S. PATENT APPLICATION

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Invention: PROCESSES FOR PREPARING CONDUCTIVE MACROMOLECULAR
POLYTHIOPHENES

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SPECIFICATION

PROCESSES FOR PREPARING CONDUCTIVE MACROMOLECULAR POLYTHIOPHENES

Field of the Invention

5 The present invention relates to a process for preparing polythiophenes using acid catalysts. More specifically, it relates to a one-step process for manufacturing electrically conductive polythiophenes from 2,5-dihalothiophenes in the presence of acid catalysts such
10 as Lewis acid, protic acid, organic acid or polymer acid in organic solvents or aqueous solution.

Background of the Invention

Conductive polymers have the physical properties of general polymers as well as the electric, magnetic and
15 optical properties of metals. Therefore, they have a wide range of applications in the fields of conventional metals and electronic materials.

Among the many interesting conductive polymers developed over the past 30 years, polyanilines, polypyrroles
20 and polythiophenes have attracted the most attention and have been used in industrial applications and academic research.

While polyanilines are advantageous due to their low cost, they also show low heat stability and weak chemical
25 resistance. In addition, the possible presence of benzidine

moieties in the polymer backbone, which might yield carcinogenic products upon degradation, have limited their application. On the other hand, polythiophenes and polyprroles are more environmentally friendly.

5 In particular, poly(3,4-alkylenedioxythiophene)s in which conductivity, thermal stability and chemical resistance are enhanced by the incorporation of alkoxy-substituents at the 3,4-positions of the thiophene ring have been developed by Bayer, Germany, and used in various
10 applications. More specially, poly(3,4-ethylenedioxythiophene) has been shown to have relatively high conductivity higher than 100 S/cm. The oxygen substituents appear to reduce the bandgap in the conducting polymer and subject it to regular condensation at the 2,5-
15 positions during polymerization. Thus, regular polycondensation and a low band gap can provide homogeneity to give high conductivity and thermal- and chemical-stability. Poly(3,4-alkylenedioxythiophene) has a wide range of applications, as follows:

- 20 1) Antistatic agent: to prevent static generated on the surface of plastic material or polymer, such as via a coating;
- 2) Condenser: for use as an alternative to electrolytes;
- 3) Coating on PCB(printed circuit board): to minimize
25 environmental pollution by replacing conventional metal

plating;

4) Organic EL(electro-luminescence) device: for use as a hole injecting layer on an ITO(indium tin oxide) substrate.

There is also growing interest in the development of synthetic processes, new polythiophene analogues and in-place industrial applications.

This invention relates to a new method for manufacturing conducting poly(3,4-alkylenedioxythiophene)s.

In general, polythiophene is prepared from the corresponding thiophene as a monomer. The known processes for the synthesis of polythiophene involve chemical or electrochemical polymerization. The typical chemical synthesis of conductive poly(3,4-alkylenedioxythiophene) involves the oxidative polymerization of 3,4-alkylenedioxythiophene with an oxidant (*Polym. Mater. Sci. Eng.* 1995, **72**, 319; *Macromolecules*, 1996, **29**, 7629; *Macromolecules*, 1997, **30**, 2582; *Synth. Met.* 1999, **102**, 967; US Patent Nos. 4,987,042 (1991) and 4,959,430 (1990)).

For example, with 3,4-ethylenedioxythiophene and an oxidant in organic solvent, conductive poly(3,4-ethylenedioxythiophene) is obtained as a powder. When the polymerization of 3,4-ethylenedioxythiophene in the presence of oxidant is carried out in an aqueous solution using a surfactant, a colloid aqueous solution of the conductive polymer can be prepared(EP 440957, 1991; EP

553671, 1993; US Patent No. 5,792,558, 1996). The average diameter of poly(3,4-ethylenedioxythiophene) particles in the dispersions is within the range of 10 nm to 1 μ m (US 5,300,575, page 2).

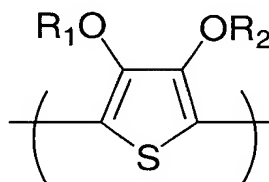
5 Another chemical process for preparing poly(3,4-ethylenedioxythiophene) from 2,5-dichloro-3,4-ethylenedioxythiophene using a blended nickel catalyst, consisting of bis(1,5-cyclooctadiene)-nickel(0), Ni(cod)₂ and 2,2'-bipyridyl, has also been reported (Polymer, 2001, 42, 7229; Polymer, 2002, 43, 711). This method is not
10 desirable for practical use in industrial applications that are expected to have a low manufacturing cost. In addition, Ni-catalyzed polycondensation of poly(3,4-ethylenedioxythiophene) requires an additional reaction
15 process to give conductive properties, a so called doping process. Polymers show conductivity in the *p*-doped state, while they have no conductivity in the *n*-doped (=dedoped) state. Polythiophenes produced by oxidative chemical polymerization are inherently conductive because the
20 oxidant serves as a dopant.

Summary of the Invention

The present inventors have developed a simple one-step process for preparing *p*-doped conductive polythiophenes from
25 2,5-dihalothiophene in the presence of acid catalysts. The

polythiophene powder has excellent inherent conductivity, higher than 255 S/cm under optimal conditions, and high thermal- and chemical-stability.

The object of the present invention is to provide a
5 process for preparing conductive polythiophenes made up of structural units corresponding to the following the general formula (1):



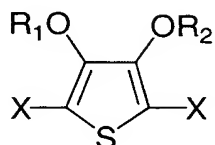
(1)

10 where, R₁ and R₂ individually represent hydrogen or a C₁~C₄ alkyl group, or together represent an optionally substituted C₁~C₄ alkylene group, preferably an optionally alkyl-substituted methylene group, an optionally C₁~C₄ alkyl or phenyl-substituted 1,2-ethylene group, a 1,3-propylene or a
15 1,2-cyclohexylene group, in the presence of polyanions.

Detailed Description of the Preferred Embodiments

The process for preparing polythiophenes from 2,5-dihalothiophenes according to the present invention grants
20 high conductivity by virtue of the acid catalyst that acts as a dopant. Acid-catalyzed polymerization has never been applied to the preparation of hetero-aromatic polythiophenes and polypyrroles.

The structural formula of 2,5-dihalothiophene, the starting monomer used in the present invention, is shown as the general formula (2):



where R_1 and R_2 are described in The general formula (1), and X is I, Br or Cl.

The polymerization in the present invention is performed by dissolving 2,5-dihalothiophene[general formula (2)] and acid in solvent and vigorously stirring the mixture at an appropriate temperature until the polymerization reaction is complete.

The polymerization time is generally between 1 and 72 hours, depending on the size of the bath, the polymerization temperature, the amount of acid, and etc. The yield and conductivity may be improved by increasing the reaction time, more than 15 hours.

There are few limitations on the type of acid used. For practical reasons, it is preferable to use inexpensive and easy-to-handle acid. Specifically, the acid that can be used include boron salt, zinc salt, tin salt, aluminum salt and iron salt as Lewis acid, the boron salt is boron trifluoride, boron trifluoride dihydrate, boron trifluoride

diethyl etherate, boron trifluoride-alcohol complex, boron trifluoride-methyl sulfide complex, boron trifluoride-phosphoric acid complex, boron trichloride, boron trichloride-methyl sulfide complex, boron tribromide, or
5 boron tribromide-methyl sulfide complex, with the boron trifluoride being the most preferable; phosphoric acid, sulfuric acid, nitric acid, hypochlorous acid, HF, HCl, HBr, and HI as a protic acid, with phosphoric acid being the most preferable; carboxylic acid or sulfonic acid as a organic
10 acid, with p-toluenesulfonic acid being the most preferable; and polystyrenesulfonic acid, polyacrylic acid, polymethacrylic acid, polymaleic acid and polyvinylsulfonic acid as polymeric acid, with polystyrenesulfonic acid being the most preferable. The acid described above can be used
15 either alone or as a mixture with one or more other acid(s). The amount of acid is determined to be 1-20 equivalents per mol 2,5-dihalo thiophene depending on the type of acid. When there is less than 1 equivalent, the reaction process is retarded to give a reaction product in low yield and low
20 conductivity, while when there is more than 20 equivalents, the high acidity makes work-up difficult and increases the production cost. In practice, the acid is used, for example, in an excess of 3 to 7 equivalents per mol 2,5-dihalo thiophene.

25 The solvents that can used in the present invention

include C₆~C₂₀ aliphatic and aromatic hydrocarbons, halogen-containing hydrocarbons, ketones, ethers, C₂~C₂₀ alcohols, sulfoxides, amides and water. These solvents may be used alone or as a mixture of two or more solvents. More specifically, C₆~C₂₀ aliphatic and aromatic hydrocarbons include alkanes such as hexane, heptane, octane, nonane and decane and alkylbenzenes such as benzene, toluene, xylene, cumene, mesitylene, phenol and cresol; halogen-containing hydrocarbons include carbon tetrachloride, chloroform, dichloromethane, dichloroethane, dibromoethane, trichloroethane and tribromoethane; halobenzenes include dichlorobenzene, chlorobenzene and the like; ketones include acetone, propanone, butanone, pentanone, hexanone, heptanone, octanone and acetophenone; ethers include diethyl ether, tetrahydrofuran (THF), dipropyl ether, dibutyl ether, methyl butyl ether, diphenyl ether, dioxane, diglyme, diethylene glycol, ethylene glycol (EG) and the like; sulfoxides include dimethylsulfoxide (DMSO); and amides include N,N-dimethylformamide (DMF), N-methylacetamide (NMAA), N,N-dimethylacetamide (DMA), N-methylpropionamide (NMPA), N-methylpyrrolidinone (NMP) and the like. The most suitable solvent is selected depending on the type of acid catalyst used. When using a Lewis acid, organic acid or polymer acid, C₆~C₂₀ aliphatic and aromatic hydrocarbons, ethers and polar solvents such as DMSO, DMF, NMP or the like are preferred,

while with inorganic acid, water or C₂~C₂₀ alcohol is preferred.

The reaction temperature of the polymerization according to the present invention is from 15°C to 180°C, or
5 the boiling temperature of the solvent used.

We will now describe the process according to the present invention in more detail.

Monomer of the general formula (2) and acid catalyst are added to the solvent, and the mixture is stirred
10 vigorously with a homo-mixer at room temperature. To ensure the formation of polymer powder, the temperature is raised to complete the polymerization reaction. After the reaction is completed, a conductive polymer of the general formula (1) is obtained as a powder. The powder is washed with water,
15 alcoholic solvent and nonpolar organic solvents to remove impurities. The resulting polythiophene powders have a range of conductivity from 19 to 255 S/cm depending on the reaction conditions, catalyst, solvent, and etc.

A free standing film of polythiophene polymerized
20 according to the present invention was prepared by casting a monomer of the general formula (2) and inorganic acid in a volatile alcoholic solvent onto a glass substrate. The film was allowed to dry at around 150°C for 24 hours in vacuum. The conductivity of the film layer is within the range of 25
25 to 35 S/cm.

According to the present invention, polythiophene is prepared by cationic polymerization in the presence of acid catalyst. Cationic polymerization is a kind of polymerization reaction: a cation is formed at the end of a monomer that has electrophilic properties, and then aromatic electrophilic substitution occurs to lead to subsequent condensation. Two strongly electron-donating substituents, alkoxy groups at the 3,4-positions, enhance the formation of cationic monomers. A narrow distribution of molecular weight, a so called low PD value (polydispersity index, $PD=M_w/M_n$), has been observed in the case of cationic polymerization relative to oxidative polymerization. Thus, the regular sequence and uniform molecular weight of polythiophenes prepared by the present invention can be retained to give excellent conductivity.

The procedure selected depends on external factors, such as, for example, the amount and kinds of acid or solvent. The following variations are intended to describe the invention, and in no way limit its scope.

Example 1: Preparation of poly(3,4-ethylenedioxythiophene) from 2,5-dibromo-3,4-ethylenedioxythiophene by Lewis acid (BF_3)

In a three-necked flask equipped with a homo-mixer, thermometer and condenser, 20.0g of 2,5-dibromo-3,4-ethylenedioxythiophene was charged into 400ml of toluene,

and then 26.0ml of boron trifluoride was added. The mixture was stirred at room temperature for 4 hours and heated to 100°C for an additional 24 hours. The temperature was then lowered to room temperature to obtain powder via filtration.

5 After washing with water, ethanol, and hexane, the powder was dried to give 12.9g of poly(3,4-ethylenedioxythiophene) which had a conductivity of 255 S/cm (pressed pellet).

Example 2: Preparation of poly(3,4-ethylenedioxythiophene) from 2,5-diiodo-3,4-ethylenedioxythiophene by Lewis acid (ZnCl_2)

10 In a three-necked flask equipped with a homo-mixer, thermometer and condenser, 20.0g of 2,5-diiodo-3,4-ethylenedioxythiophene was charged into 400ml of xylene and 60.0g of ZnCl_2 was added. The mixture was stirred at room
15 temperature for 3 hours and then heated to 140°C for an additional 20 hours. The techniques for purification, evaluating conductivity, and preparation of soluble powder were similar to those discussed in example 1. The 13.6g of poly(3,4-ethylenedioxythiophene) obtained had a conductivity
20 of 155 S/cm (pressed pellet).

Example 3: Preparation of poly(3,4-dimethoxythiophene) from 2,5-dibromo-3,4-dimethoxythiophene by Lewis acid (BF_3)

25 In a three-necked flask equipped with a homo-mixer, thermometer and condenser, 20.0g of 2,5-dibromo-3,4-

dimethoxythiophene was charged into 400ml of toluene, and then 26.0ml of boron trifluoride was added. The mixture was stirred at room temperature for 3 hours and then heated to 120°C for an additional 24 hours. The reaction temperature was lowered to room temperature, to obtain a powder via filtration. After washing with water and ethanol three times, the powder was dried to give 9.2g of poly(3,4-dimethoxythiophene), which has a conductivity of 180 S/cm (pressed pellet).

10

Example 4: Preparation of poly(3,4-ethylenedioxythiophene) using inorganic acid (H₃PO₄) in aqueous solution

In a three-necked flask equipped with a homo-mixer and condenser, 3.0g of 2,5-dibromo-3,4-ethylenedioxythiophene was charged into 78ml of distilled water, and then 12.6ml of H₃PO₄ (85%) was added. The mixture was heated to 85°C for 9 hours. After the reaction temperature was lowered to around 10°C, the reaction mixture was poured into a mixture of aqueous sodium bicarbonate (30%, 300ml) and chloroform (600ml). The resultant mixture was stirred for 9 hours and then heated to 100°C for an additional 48 hours. The techniques for purification, evaluating conductivity, and preparing the soluble powder were similar to those discussed in an Example 1. The 1.1g of poly(3,4-

ethylenedioxythiophene) obtained had a conductivity of 57 S/cm.

Example 5: Free-standing poly(3,4-ethylenedioxythiophene)

5 film

A 1.0g portion of 2,5-dibromo-3,4-ethylenedioxythiophene and 10.6ml of H_3PO_4 (85%) were added to 50ml of ethanol. The resultant mixture was vigorously stirred at room temperature for 10 minutes and knife-coated
10 onto glass using a hand coater (wet film thickness 25 μm). The coated glass was placed in a vacuum oven and heated at 150°C to completely evaporate the solvent. It was further heated at the same temperature for 48 hours. Films prepared in this manner had a conductivity of 35 S/cm.

15 Example 6: Preparation of poly(3,4-ethylenedioxythiophene) using a mixture of protic acid (H_3PO_4) and polymeric acid (PSSA)

DMSO (100ml) was added to a three-neck flask, and 2,5-dibromo-3,4-ethylenedioxythiophene (3.0g) and H_3PO_4 (85%)
20 (5.0ml) and polystyrenesulfonic acid (10.5g) were added. As the reaction temperature was slowly raised to 140°C, the resultant mixture was vigorously stirred for 24 hours. After the reaction temperature was lowered to room temperature, the reaction mixture was neutralized with
25 chloroform (600ml) and aqueous sodium bicarbonate solution,

and the resultant mixture was stirred for an additional 2 hours. The reaction mixture was filtered to obtain powder, which was washed with water and ethanol three times and dried to give conductive macromolecular poly(3,4-
5 ethylenedioxythiophene) (0.40g). The polymer was formed into a pellet had a conductivity of 19 S/cm.

According to the present invention, conductive polythiophene made up of structural units of The general
10 formula (1) can be prepared by cationic polymerization from 2,5-dihalothiophene in the presence of acid catalyst. The conductive polythiophenes prepared by the present invention have good conductivities in the range of 19-255 S/cm.